NEW YORK UNIVERSITY
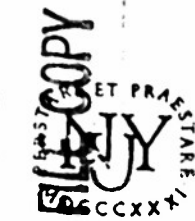
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COSMIC RAY PROJECT
PROJECT No. 101
REPORT No. 101.16

Physical Development of Nuclear Emulsions

JUNE 1, 1953
Contract No. N6 ONR 279 T.O. 2

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COSMIC RAY PROJECT

PHYSICAL DEVELOPMENT OF NUCLEAR EMULSIONS

Project No. 101

Report No. 101.16

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ABSTRACT

The method of physically developing Jlford G5 unloaded nuclear emulsion plates with an emulsion thickness of 200 microns is given. Formulas containing the processing time and the optimum concentrations of the various components of the developer which were experimentally determined are also given. Results and advantages of this method of physical development are then compared to those obtained from the conventional method of chemically developing the nuclear emulsions.

ACKNOWLEDGMENTS

CONTENTS

I. INTRODUCTION

Ordinary photographic emulsion consists of a suspension of silver bromide in gelatin with the addition of a little silver iodide to improve its sensitivity. The so-called "nuclear emulsion" is a photographic emulsion with a very high concentration of silver halide to render it capable of recording ionizing particles. In order to observe under a microscope the recorded tracks produced in the nuclear emulsion by ionizing particles, it is necessary to develop the latent image in the emulsion as in ordinary photography. There are two methods of development: "chemical development" and "physical development."

Chemical development is the conventional method of developing both ordinary photographic and nuclear emulsions with organic reducing agents. This is well known and will not be discussed here.

Physical development, although not commonly known except in the photo-engraving industry, is essentially similar to the method employed in developing the plates of the wet collodion process[1], the first highly successful negative photographic process, about a hundred years ago. The developing bath contains, in addition to a reducing agent, free silver ions and a weak acid. It is in reality a silver plating solution. Compared to chemical development, this

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1. C. B. Neblette, Photography, Its Principles and Practice (Van Nostrand, New York, 1938), p. 12.

method requires a much longer period of development and greater attention to detail. Notwithstanding these setbacks, physical development has been found[2] to possess several advantages, especially the production of an extremely fine grain, in ordinary photography. The possibility of utilizing this method and some of its advantages, which will be explained in the next section, in the processing of nuclear emulsions was explored in the work reported here.

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2. A. F. Odell, Camera 46, 217 (Phila., 1933).

II. THEORY

Development is the process by which the latent image in the photographic emulsion is rendered visible by a reducing agent or developer. This consists of the formation about or the deposition upon the submicroscopic silver specks or development centers of the silver halide grains composing the latent image in the emulsion sufficient additional silver to produce a visible image. In the case of chemical development, the additional silver results from the reduction of the exposed silver halide grains in the emulsion to silver. In the case of physical development, the additional silver is acquired from the developing solution and is deposited upon the silver specks of the halide grains. In either case, the process involves the catalyzed reduction in solution of the silver ions to metallic silver about the silver specks, i.e.,

$$R \longrightarrow R \text{ (oxidized)} + e$$

$$Ag^+ + e \longrightarrow Ag$$

where R is the reducing agent[3].

Sheppard[4] discovered that the silver specks on the silver halide grains are formations of silver sulfide produced under alkaline conditions by isothiocyanates in the photographic gelatin

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3. T. H. James and G. C. Higgins, Fundamentals of Photographic Theory (Wiley and Sons, New York, 1948), ch. 5.
4. S. E. Sheppard, Phot. J. 65, 380 (1925).

reacting with silver bromide to form double compounds of relatively low solubility. In conventional development, these specks on a silver halide grain initiate the reduction of the silver ions in solution with the rate of reduction increasing continuously until the entire grain has been reduced to metallic silver. Various theories have been offered by different investigators[5,6] to explain latent image formation. This formation, however, does not occur similarly in physical development, in which case the silver specks act as centers for the deposition of additional colloidal silver from the developing solution, thus resulting in extremely fine grains developed independently[7] of the original size of the silver halide grains.

Although it has been found[8,9] that sensitivity is a function of grain size, i.e., the sensitivity is greater for larger grains, producing extremely fine grains has the advantage of improving[10] measurements of grain densities of particle tracks in nuclear emulsions. Such measurements of grain densities give measures of ionization produced by the particles and contribute[11] to track

5. C. E. K. Mees, The Theory of the Photographic Process (Macmillan, New York, 1942), ch. 8.
6. J. W. Mitchell, Fundamental Mechanisms of Photographic Sensitivity, J. W. Mitchell, ed. (Butterworths, London, 1951), p. 242.
7. H. Arens and J. Eggert, Z. Elektrochem. 35, 728 (1929).
8. T. Svedberg, Phot. J. 62, 186, 310 (1922).
9. F. C. Toy, Phil. Mag. 44, 352 (1922).
10. P. H. Fowler and D. H. Perkins, Ref. 6, p. 340.
11. B. Peters, Progress in Cosmic Ray Physics, J. G. Wilson, ed. (Interscience, New York, 1952), p. 191.

identification. With conventional development of nuclear emulsions, exceeding an upper limit of grain density of about 50 grains per 100 microns of track length will render an appreciable number of grains unresolvable.

The silver halide grains in nuclear emulsions, when traversed by ionizing particles, usually have a large number of development centers per grain. The grains whicn have not been traversed by ionizing particles and which compose the background fog, however, have only several centers per grain. This can be seen in the electron photomicrographs in Fig. 1 and 2. These enlarged electron photomicrographs show latent images which have been physically developed very moderately with gold by Hoerlin[12]. The latent images are results of alpha-particle exposure. The smaller size of the development centers on the exposed grains as compared to the size of those on the fog grains is due to the rapid traversal of the alpha-particles. According to Svedberg and Andersson[13], the development centers obey Poisson's law of distribution. A reduction of fog background as obtained in chemical development where the developed grain is not independent of the size of the original halide grain should consequently be possible in physical development and result in improved track recognition[14].

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12. H. Hoerlin, Ansco, Binghampton, New York.
13. T. Svedberg and H. Andersson, Phot. J. 61, 325 (1921).
14. R. W. Berriman, Ref. 6, p. 272.

Fig. 1

Enlarged electron photomicrograph of latent image
physically developed very moderately with gold.
The two grains heavily clustered with development
centers appearing as black spots have been traversed
by alpha-particles. The other grains having only
several centers are background fog grains. The
smaller size of the development centers on the
exposed grains as compared to the size of those on
the fog grains is due to the rapid traversal of the
alpha-particles. Total magnification is
approximately 80-120,000X.

Fig. 2

Enlarged electron photomicrograph of latent image
physically developed very moderately with gold.
The grain with the numerous development centers
has been traversed by an alpha-particle. Part of
two fog grains without any centers can be seen
on the right.

There are two types of physical development: pre-fixation physical development and post-fixation physical development. The former means that development can be performed in the presence of the unexposed silver halide of the emulsion whereas the latter means that development can occur after the unexposed silver halide has been dissolved in a sodium thiosulfate solution. In post-fixation physical development of nuclear emulsion, the latent image is very likely to fade because (a) the very fine silver specks are reactive and oxidize very easily, with the complex-forming action of the fixing agent increasing the oxidation[15,16], and (b), to a smaller degree, the acquisition of energy by the electrons of the silver specks sufficient to re-enter the conductance band of the crystal causes the thermal ejection of these electrons from the specks, rendering some of them undevelopable through the loss of silver ions with a consequent reduction in size[17] of the specks.

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15. Ref. 5.
16. C. B. Neblette, Photography, Its Materials and Processes (Van Nostrand, New York, 1952), p. 188.
17. A. Beiser, Phys. Rev. 80, 112 (1950).

III. MATERIALS AND TECHNIQUE

Ilford G5 unloaded nuclear emulsion plates with a plate size of
2 x 3 in s and an emulsion thickness of 200 microns were used in
this experiment. Table I gives the compo: ion[18] of this dry
emulsion.

Table I

Element	grams/cm^3	atoms/cm^3 x 10^{22}
Silver	2.025	1.17
Bromine	1.465	1.15
Iodine	0.057	0.03
Carbon	0.30	1.51
Hydrogen	0.049	2.93
Oxygen	0.20	0.75
Sulfur	0.011	0.02
Nitrogen	0.073	0.31

The composition values, however, vary with atmospheric humidity
because of the hygroscopic nature of gelatin.

Exposure of the nuclear emulsion plates was performed by placing
them edgewise over a 1 millicurie polonium-beryllium neutron source
for about a week. The fastly irradiated neutrons produced in the
emulsion latent images of recoil proton tracks or nuclear disruptions.
Since these images fade appreciably in less than six weeks, with the
fading rate decreasing with time[19,20], the plates were processed as
soon as possible after exposure to the irradiation.

18. A. Beiser, Rev. Mod. Phys. 24, 273 (1952).
19. G. P. S. Occhialini and C. F. Powell, Nature 159, 186 (1947).
20. G. Albouy and H. Faraggi, Ref. 6, p. 290.

To determine the possibility of physical development of the nuclear emulsion plates, Odell's[21] revised formula for the physical development of ordinary photographic emulsions was used. However, for any result to occur at all, the processing time had to be increased considerably because of the thickness of the emulsion. The effective processing time had to be determined by trial and error and not by inspection. Unlike the ordinary photographic film where the first appearance of an image visible to the naked eye during development can usually be observed under a safelight, the microscopic image in the nuclear emulsion can be observed only after the processing has been completed. An attempt to improve results was made by varying the concentrations of the different components of the developer for the purpose of obtaining the optimum combination. Odell's revised formula is given in Table II.

Table II

Forebath
Potassium iodide	10 grams
Sodium sulfite, anhydrous	25 grams
Water to make	1 liter

Developer
Stock solution:
Sodium sulfite, anhydrous	100 grams
Silver nitrate	16 grams
Sodium thiosulfate	160 grams
Water to make	1 liter

Working solution:
Stock solution (above)	200 ml
Water to make	1 liter
Amidol	1.5 grams

21. A. F. Odell, Camera 54, 145 (Phila., 1937).

The forebath in the formula was discovered earlier by Lüppo-Cramer[22] to be effective in decreasing the developing time. The potassium iodide serves as the restrainer, i.e., it decreases the developing rate to insure that the developer acts only on the latent image and not on the unexposed silver halides of the emulsion, which otherwise would produce fog. Oxidation of the developer by contact with atmospheric oxygen is prevented by the sodium sulfite which acts as the preservative. A more important function of the sodium sulfite is that of a pH buffer, i.e., it insures the alkalinity of the developing solution, a controlling factor in development. Amidol is the developing agent, which is effective in a sulfite solution even without the addition of an alkali. The silver nitrate supplies the larger share of the silver ions in the developing solution. Sodium thiosulfate dissolves silver halide during development without seriously affecting the latent image and, hence, supplies the remaining share of the silver ions in the developing solution for the formation of the final silver image. Its concentration, according to Odell, is a significant factor in development. Reducing the concentration would induce some chemical development; increasing it would retard physical development. In this respect, it should be mentioned that fresh, clear crystals of sodium thiosulfate are to be used, since the efflorescing effect of the fresh crystals during exposure to the air results in an increase

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22. Lüppo-Cramer, Phot. Ind., 401 (Berlin, 1917).

in the sodium thiosulfate content by weight. This effect of efflorescence is easily detected by the white or opaque appearance of the crystals.

To prepare the stock solution, the sodium sulfite is dissolved first in about 300 milliliters of water (warmed to about 50°C if necessary) and the silver nitrate in about 200 milliliters of water. The silver solution is then added slowly to the sulfite solution with constant stirring until the precipitate is dissolved completely. Sodium thiosulfate is finally added with additional water to make a liter. This stock solution has good keeping properties as compared to the working solution which must be prepared just before using.

Table III gives the formula used for the non-hardening acid fixing bath.

Table III

Fixing bath
Sodium thiosulfate	400 grams
Ammonium chloride	14 grams
Sodium bisulfite	15 grams
Water to make	1 liter

The sodium thiosulfate is the usual fixing agent which removes the residual silver halide after development. Ammonium chloride tends to reduce the fixing time[23]. Sodium bisulfite is the acid sulfite which neutralizes any trace of alkali carried over from the developer, thus preventing the probable staining of the emulsion

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23. B. Stiller, M. M. Shapiro, and F. W. O'Dell, Bull. Amer. Phys. Soc. 26, No. 6, 16 (1951).

caused by the oxidation of the developing solution in the emulsion.

The processing of the nuclear emulsion plates was performed in a darkroom ventilated by means of a blower and illuminated with a Wratten series No. 2 safelight. By operating the blower at proper times and keeping the cold water running, it was possible to maintain the room temperature below 20°C and the relative humidity sufficiently high for effective processing. This does not apply, however, to warm days when processing of thick emulsions is practically impossible without elaborate equipment.

For immersion of a plate in solution, a stainless steel tray with the capacity of a liter was used. Glass trays were also used; however, it should be mentioned that only those types of trays which are inert to the silverplating action of the developing solution, e.g., porcelain, glass, plastic, hard rubber, and stainless steel, may be used. Metals with the exception of stainless steel should be avoided.

Temperature control of the solution was effected by placing the tray containing the solution in a large water-jacketed tray. By gradually varying the temperature of the water in the large tray, the temperature of the solution was controlled accordingly.

Agitation was accomplished by stirring the solution gently and intermittently with a stirring paddle. This mild agitation was kept to a minimum in the developing solution to prevent the creation of a development gradient throughout the thick emulsion and to avoid increasing the oxidation of the developer. An attempt with nitrogen agitation was made by passing nitrogen into the solution through gas

dispersers, but this was unsatisfactory in view of the already weakened condition of the emulsion.

Dilution of the solution in a tray with the plate immersed in it was performed by gently transferring about three-fourths of the solution into another similar tray, taking precautions not to shock or damage the plate, and filling the remaining fourth with water. This was repeated four or five times, and each time the diluted solution was thoroughly mixed and brought to the proper temperature before the plate was transferred into it.

Washing after fixation was done by immersing the plate in a tray containing two liters of water and about 15 drops of glycerine. The purpose of the glycerine is to soften the emulsion, thus reducing any strain set up by the removal of the residual silver halide. The number of changes of water required was determined by using a sodium thiosulfate indicator solution, the formula for which is given in Table IV.

Table IV

Sodium thiosulfate indicator solution

Water	150 ml
Potassium permanganate	0.3 gram
Sodium hydroxide	0.6 gram
Water to make	250 ml

Presence of sodium thiosulfate will change the violet color of the permanganate in a drop of the solution to orange or yellow within a minute, otherwise the violet color will remain the same. The last

wash was followed by a ten-minute soaking of the plate in water containing several drops of a wetting agent. This soaking reduces the surface tension and facilitates the outward diffusion of water from the interior of the emulsion. Agitation was accomplished as before.

Drying of the plates was accomplished by placing them in a horizontal position in the darkroom for several days at a high relative humidity. The plates were partially covered to minimize the deposition of dust particles on the surface of the emulsion and to reduce the rapid surface evaporation of water caused by circulating air currents. The greater the difference between surface evaporation and outward diffusion of water, the greater will be the strain experienced by the emulsion.

IV. RESULTS AND DISCUSSION

The optimum temperature and time obtained for each step in the processing procedure is given in Table V.

Table V

Procedure	Temperature	Time
Forebath	17°C	2-1/2 hours
Rinse	12°C	1 hour
Developing solution	18°C	18 hours
Rinse	12°C	1 hour
Fixing solution	17°C	24 hours
Wash	12°C	24 hours
Dry	19°C	4 days

To prevent the occurrence of reticulation, a condition of distortion caused by abrupt changes of temperature and concentration of solution[24] and indicated by irregular swelling and rupture of the emulsion, it was found necessary to lower the temperature of the solutions gradually to 12°C and to dilute them gradually before each rinse. The dilution time for each solution is included in the time indicated in Table V. The time is about one-half hour for the forebath, two hours for the developing solution, and four hours for the fixing solution. If the plates were rinsed at the same temperature as that of the previous step, the probability of reticulation even after gradual dilution would be greater than that at the reduced temperature.

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24. Ref. 5.

The temperature of the developing and fixing solutions were lowered to 12°C before the plates were transferred into them. This permitted penetration of the solutions before the resumption of full activity at the higher temperatures and contributed to uniform development. For thicker emulsions, it would be necessary to go below the temperature of 10°C. Below this temperature, the decrease of activity of the developer is greater than the rate of penetration. If the temperature is lowered to 5°C, penetration becomes difficult[25].

The rapid oxidation of the amidol developer at the temperature specified necessitated several changes of the developing solution. These changes were made approximately by the hour for the first five or six hours. Development for the remaining time hence occurred at a lowered rate. Mixing of the amidol into the solution was done immediately before the solution was used. After mixing in the amidol, the solution gave a pH of 7.2.

No change of solution was required for the fixing stage; however, two liters of fixing solution were used for each plate. Immediately before fixation and while the plate was being rinsed in water, it was found convenient to wipe off with care the excessive layer of silver deposit on the surface of the emulsion. Wiping was done with cotton immersed in the water.

In washing, three or four changes of water were required

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25. C. C. Dilworth, G. P. S. Occhialini, and L. Vermaesen, Ref. 6, p. 297.

according to the sodium thiosulfate indicator solution used.
Attempts at washing with running or trickling water produced
deleterious effects on the emulsion.

Rapidly lowering the relative humidity of the room after one or
two days of drying was observed to cause not only distortion but the
stripping of the emulsion from its glass backing. Glass covered
containers were found convenient in storing the plates after drying
and in preventing abrupt changes of relative humidity and temperature
from affecting the emulsion while in storage. Prior to storing the
plates, it was necessary to remove the remaining surface deposits of
silver by wiping with cotton moistened in methyl alcohol.

In varying the concentration of each component of the developer,
the variation is limited by the solubility of some of the components.
Sufficient variation was permitted however to give improved results,
especially in the uniformity of development. The concentrations of
the different components were first varied simultaneously until an
approximately good combination was obtained.

The results of the background density as a function of
concentration are indicated by the bar graphs in Fig. 3 to 6. The
length of a particular bar represents the extent of the grain density
fluctuations[26] in a certain volume of emulsion developed at the
concentration indicated. The values were obtained with a Bausch and

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26. P. E. Hodgson, Brit. J. Appl. Phys. $\underline{3}$, 11 (1952).

Fig. 3 to 6

Results of the background density of physically
developed nuclear emulsion plates as a function of
concentration of the developer component indicated.
The length of a particular bar represents the extent
of the grain density fluctuations in a certain volume
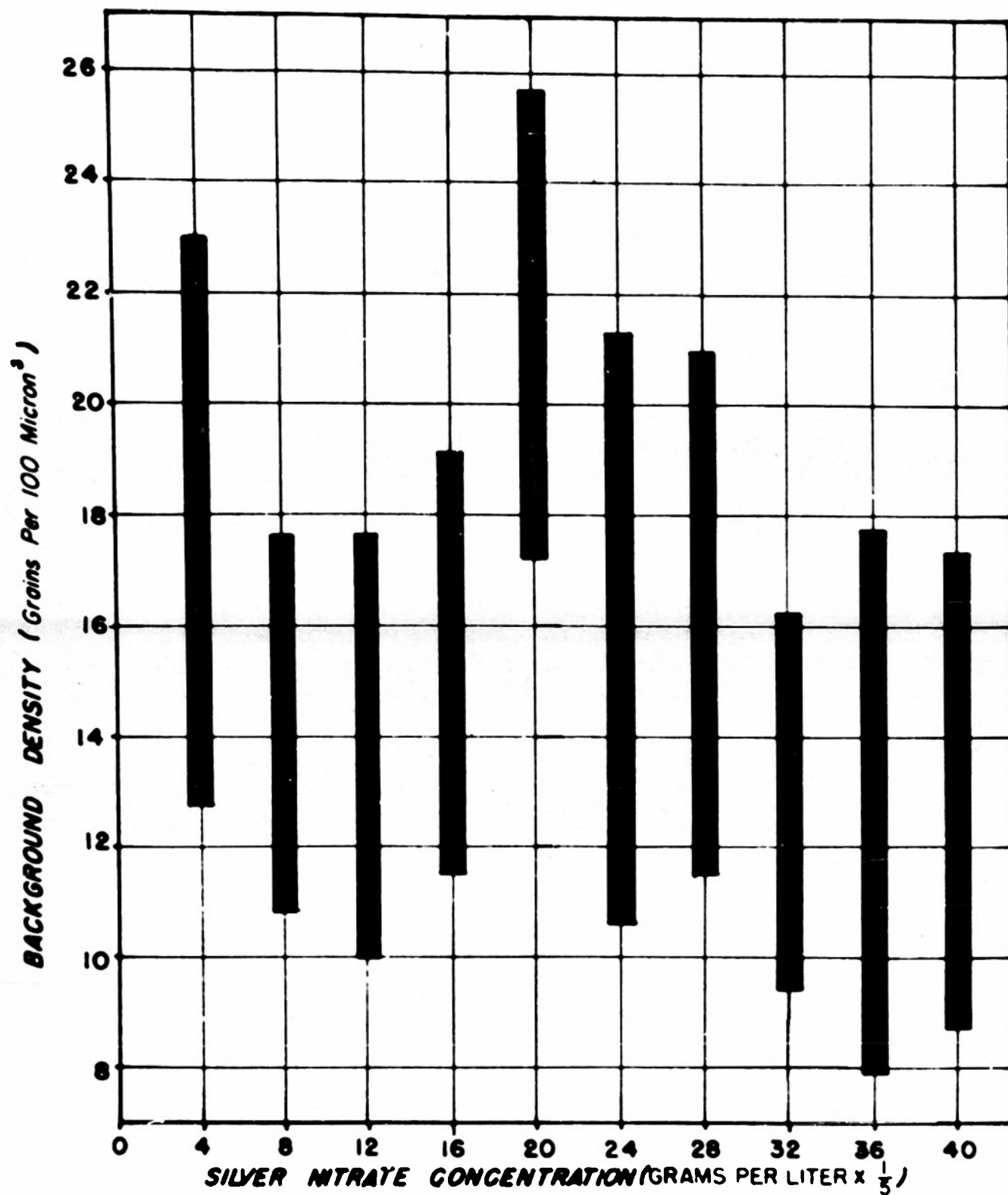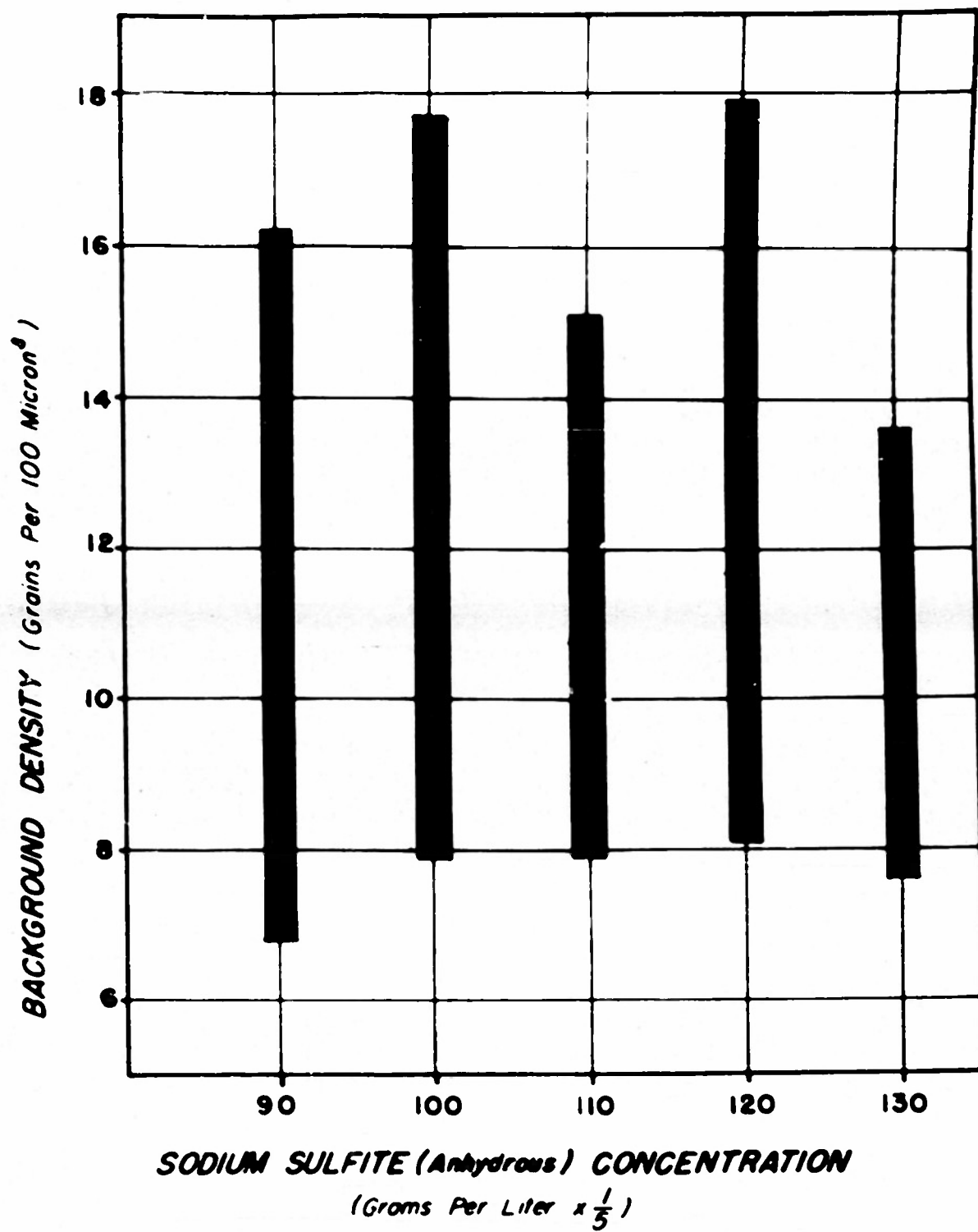of emulsion devoloped at the concentration indicated.

FIGURE 3

BACKGROUND DENSITY (Grains Per 100 Micron^2)

SODIUM SULFITE (Anhydrous) CONCENTRATION
(Grams Per Liter x $\frac{1}{5}$)

FIGURE 4

FIGURE 5

BACKGROUND DENSITY (Grams Per 100 Micron³)

AMIDOL CONCENTRATION (Grams Per Liter)
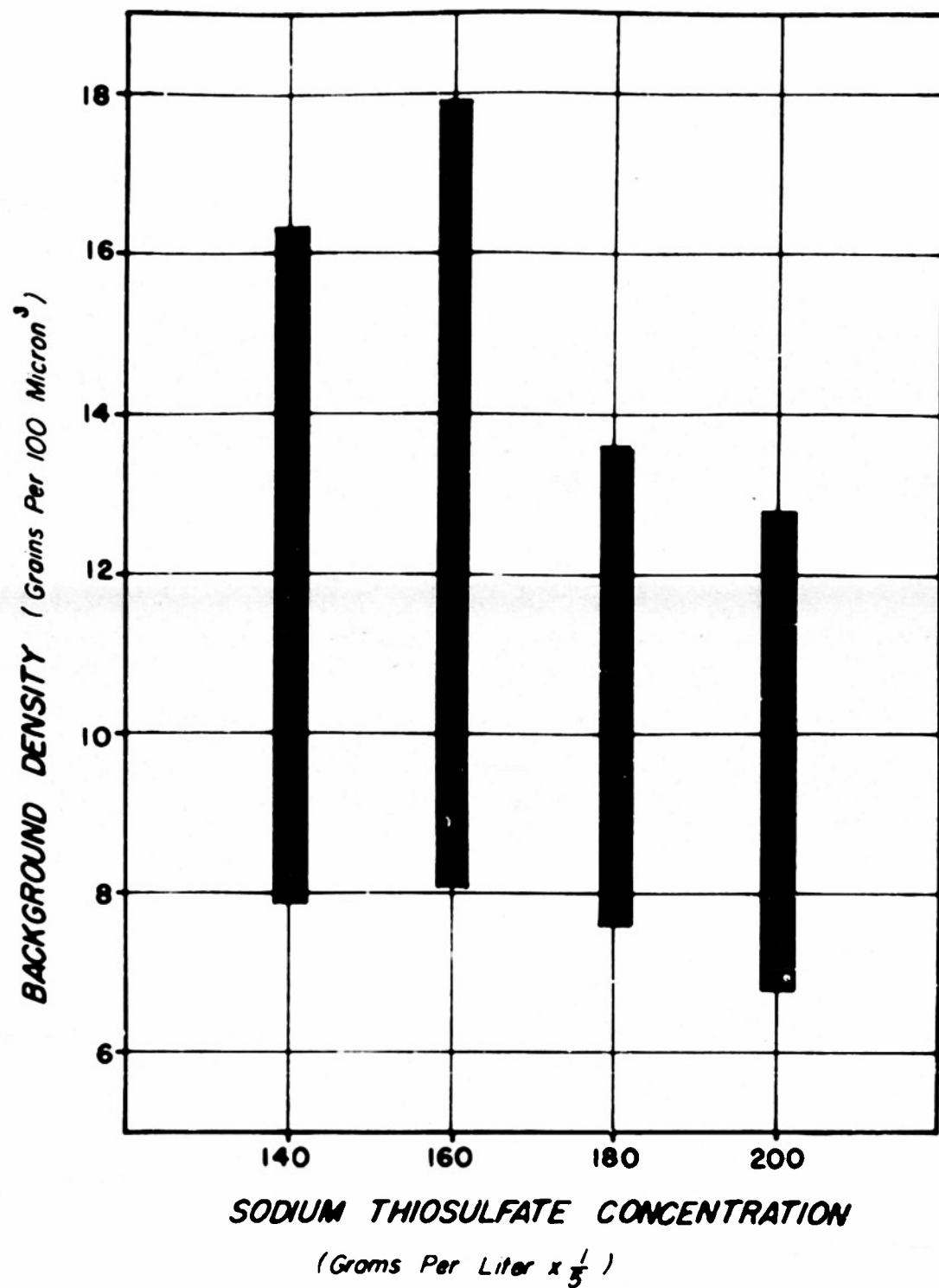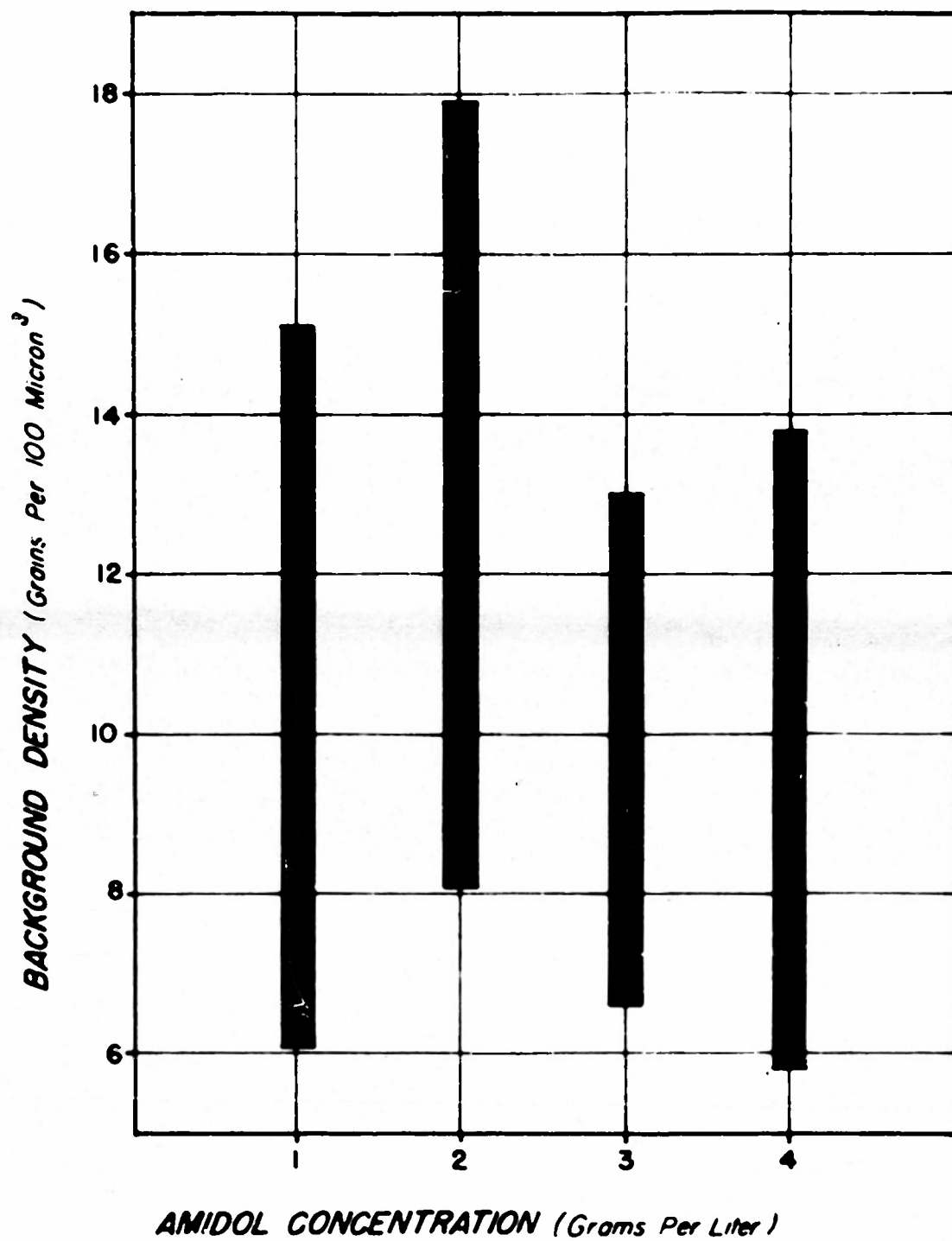
FIGURE 6

Lomb microscope focused through a 97X oil-immersion objective and a
10X ocular with a grid scale containing squares each having a
calibrated area of 52.8 micron^2. Sixteen of these squares centrally
located on the grid were used in the grain-count. Grains in the
emulsion enclosed under each square were counted separately. The
depth of field was estimated to be 1 micron. By determining the
mean value of the sixteen counts and calculating the deviation from
the mean with the standard deviation formula

$$\sigma = \sqrt{1/n \sum_i (x_i - \bar{x})^2} \qquad (i = 1,2,\ldots,16),$$

where σ is the deviation, n the total number of counts, x_i the
value of the ith count, and $\bar{x}$ the mean value of the total number of
counts, the extent of the grain density fluctuations in the volume in
question was derived. The value expressing the number of grains per
52.8 micron^3 was then converted to give the number of grains per
100 micron^3. To minimize the probability of locating for the grain-
count areas which have been subjected to considerable distortion
during processing, areas contiguous to reasonably straight recoil
proton tracks were chosen, with such tracks being used as indicators
of distortion and of the condition of development. The variation in
manufacture from batch to batch[27] of the same type of nuclear
emulsion plates may have slightly affected the results. The

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27. A. C. Coates, Ref. 6, p. 320.

difficulty of obtaining accurate grain-counts contributed to the
results a percentage of errors of which a quantitative estimate
cannot be given, since the errors of grain-counting are superimposed
over the random fluctuations of the grain density.

In Fig. 3, the bars for the 4/5, 20/5, and 28/5 grams of silver
nitrate concentration represent the results of three plates processed
simultaneously and under similar conditions except for the concentra-
tion. Considered separately, they suggest a pattern closely
resembling that formed by the remaining bars. The suggested pattern
is believed to give the appropriate representation of the results,
and the difference of representation may be attributed to processing
errors. With this in mind, it can be seen that the background
density increases with increase in silver nitrate concentration until
the concentration of 20/5 or 24/5 grams is reached when the density
begins to fall off. Maximum background fog is undesirable in track
recognition and low concentration of silver nitrate may contribute to
nonuniformity of development by supplying insufficient silver ions in
solution. Hence a concentration of 36/5 or 40/5 grams would appear
to offer optimum results.

In Fig. 4, the background density increases with increase in
sodium sulfite concentration until the concentration ranging from
100/5 to 120/5 grams is reached. Since one purpose of the sodium
sulfite is to prolong the life of the developer by preventing its
oxidation and since high background density indicates the

effectiveness of the developer, the most effective concentration will be that which gives maximum density. Too low a concentration will affect its pH buffering action. If its concentration is too high, the developer will be too rapid for uniform development of thick emulsions.

The results of the variation of sodium thiosulfate concentration in Fig. 5 appear to agree with the findings of Odell as mentioned earlier, with 160/5 grams being the optimum concentration. As stated by Odell, a lower concentration induces some chemical development and a higher concentration retards physical development. The reduced densities shown in the figure corroborate Odell's findings.

Fig. 6 indicates that 2 grams is the most effective concentration used for the developing agent. The higher concentrations also appear to retard development. This is probably caused by the rapid deposition of silver on the surface of the emulsion and thus impeding the penetration into the emulsion of fresh developer.

From observation of the processed plates, the concentrations suggested above gave the best results. The optimum concentrations are listed in Table VI, which gives a modified formula for the developer.

Table VI

Developer
    Stock solution:

Sodium sulfite, anhydrous	120 grams
Silver nitrate	36 grams
Sodium thiosulfate	160 grams
Water to make	1 liter

    Working solution:

Stock solution (above)	200 ml
Water to make	1 liter
Amidol	2 grams

For comparison with chemical development, results from chemical development of the same type of plates were obtained with the processing procedure given in Table VII.

Table VII

Procedure	Temperature	Time
Presoaking (water)	9°C	1 hour
Developer penetration (D19 diluted 1:1)	12°C	2/3 hour
Development (D19 diluted 1:6)	17°C	1 hour
Acid stop bath (1%)	8°C	1 hour
Fixation (30% hypo)	14°C	18 hours
Washing	12°C	24 hours

In Table VIII, the results obtained from two plates physically developed with the optimum and near optimum developer concentrations respectively are compared to those from two chemically developed plates separately developed.

Table VIII

	Chemical	Physical
Background density (grains per 100 micron^3)		
Plate No. 1	9.6 to 20.6	8.1 to 17.9
Plate No. 2	8.5 to 18.3	7.9 to 15.1
Average track width (microns)		
Plate No. 1	0.7 ± 0.2	1.4 ± 0.3
Plate No. 2	0.7 ± 0.2	1.3 ± 0.1

The average track width instead of the average grain density along a track was obtained because the recoil proton tracks were produced by too heavily ionizing particles to permit accurate grain-counting. The width was obtained from nine measurements made along a

reasonably uniform middle section of a long track. Since the measurements were made solely for the purpose of comparison, no effort was made to measure at an exact distance from the end of a track to account for the energy loss. The measurements were made with a 10X micrometer ocular attached to the microscope.

An enlarged photomicrograph of a portion of a chemically developed nuclear emulsion plate and that of a physically developed plate are shown in Fig. 7 and 8 respectively. Both photomicrographs were taken with the same magnification of 970X and with high contrast film. By comparing the two figures, the lack of control of contrast in the method of physical development can be observed.

Fig. 7

Enlarged photomicrograph of a portion of a
chemically developed nuclear emulsion plate.
A section of a recoil proton track is shown
against the background fog. Total
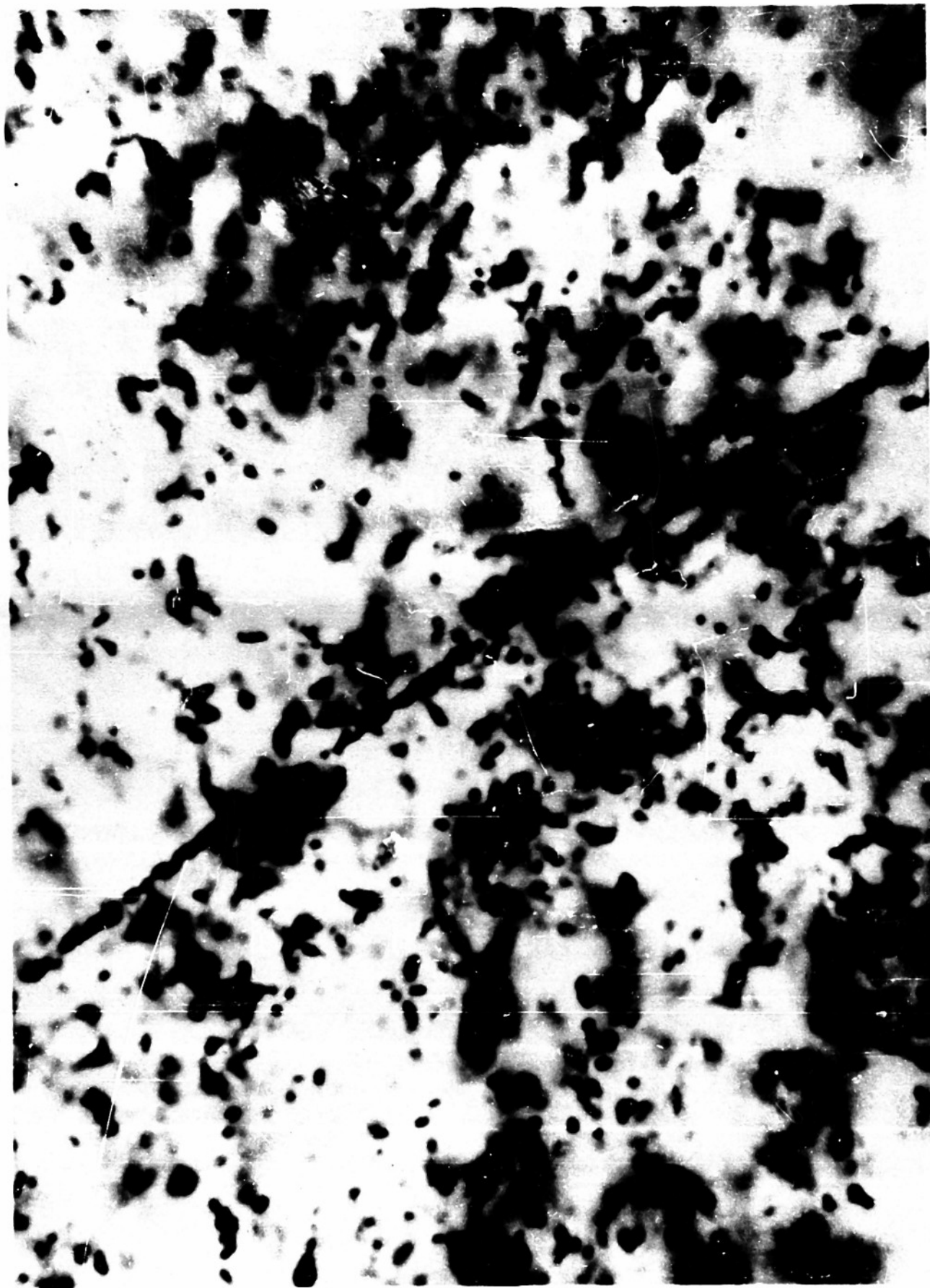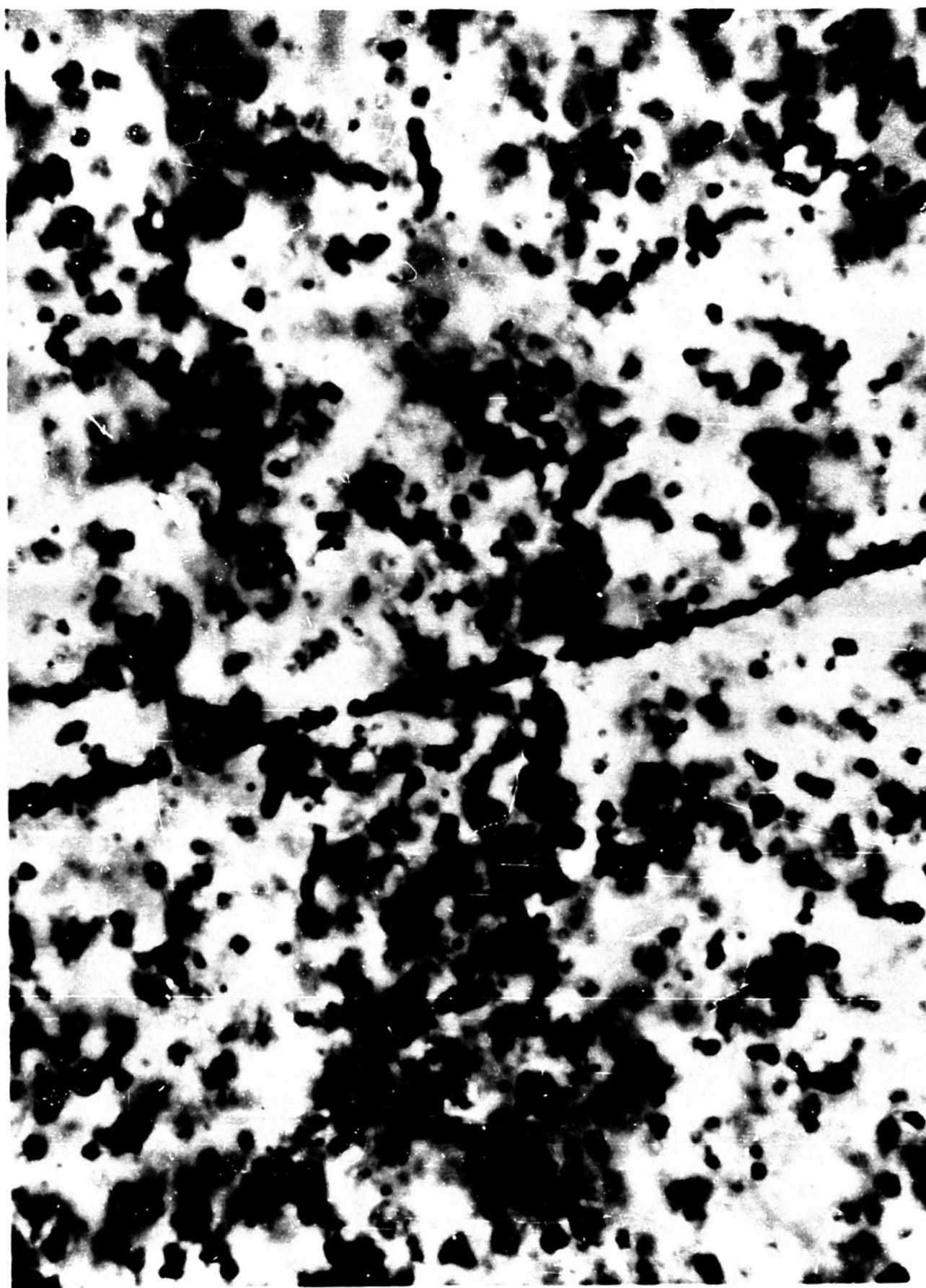magnification is approximately 4,850X.

Fig. 8

Enlarged photomicrograph of a portion of a

physically developed nuclear emulsion plate.

A section of a recoil proton track is shown

against the background fog. Total

magnification is approximately 4,850X.

V. CONCLUSIONS

The results of the experiment given in the previous section indicate the differences between the methods of physical development and chemical development of nuclear emulsions. Physical development is shown to possess the advantage of producing a wider track, in fact, a track approximately twice the width of that obtained with chemical development. This advantage, however, is shown to be partially nullified by the lack of control of contrast with physical development. Both methods of development give approximately the same density of background fog. In chemical development, background fog may be reduced with moderate development. The same can be said of physical development as can be seen in Fig. 1 and 2. However, moderate physical development of thick nuclear emulsions without risking nonuniformity of development was found difficult because of the long processing period required for physical development as compared to the short processing period required for chemical development.

The processing time indicated in the results for the physical development of nuclear emulsions is only for an emulsion thickness of 200 microns. For thicker emulsions, the processing time may become prohibitive. Whether any advantage gained by this method outweighs the expenditure of so much time is questionable. If a way can be found to reduce the processing time, however, this method will be desirable.

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5. R. W. Berriman, Ref. 1, p. 272.

6. A. C. Coates, Ref. 1, p. 320.

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